

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 14-Mar-02	3. REPORT TYPE AND DATES COVERED Final Report, 02-Oct-98 - 31-Dec-00		
4. TITLE AND SUBTITLE Chemical Plume Tracing: Insects as Model Navigators		5. FUNDING NUMBERS N00014-98-1-0820		
6. AUTHOR(S) Dr. Ring Cardé, University of California, Riverside 92521 Dr. Jay Farrell, University of California, Riverside 92521				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Office of Naval Research 800 N Quincy St. Arlington, VA 22217-5000		8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSORING / MONITORING AGENCY REPORT NUMBER		
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Distribution Unlimited				
13. ABSTRACT (Maximum 200 words) Control of robotic vehicles maneuvering upwind along an odor plume, generated by pollutant sources or unexploded ordnance, so that they discover the odor's source is an unsolved problem. Our goals have been (1) to understand how flying insects reliably locate distant upwind sources of odor and (2) develop corresponding principles for the design of planning systems that can guide vehicles to accomplish the same task. We first determined in wind tunnel trials how the fine-scale structure of odor plumes modulates such orientation in flying insects. Encounter of filaments of odor at rates of 10 Hz or higher aims the course more toward due upwind and modulates forward velocity. We then treated a virtual vehicle and virtual odor plume that simulates odor dispersal in a varying wind field. This simulation was used to analyze performance statistics of alternative plume-tracing strategies. Plume-tracing strategies were developed based on ideas inspired by moth experiments, physical principles, and engineering methods. Some of these strategies exceed the performance of insect models by using less time (and therefore energy) to localize the odor's source.				
14. SUBJECT TERMS Odor, plume tracing, insect model.		15. NUMBER OF PAGES 5		
		16. PRICE CODE		
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL	

20020322 163

GRANT # N00014-98-1-0820

PRINCIPAL INVESTIGATORS: Ring T. Cardé and Jay A. Farrell

INSTITUTION: University of California, Riverside

GRANT TITLE: Chemical Plume Tracing: Insects as Model Navigators

AWARD PERIOD: 31 August 1998 - 31 December 2001

OBJECTIVE: Discover the principles of navigation used by flying insects to find distant, point-sources of odors. Apply these principles to robotic systems designed to find point sources of anthropogenic chemicals such as those emitted from buried ordinance.

APPROACH: (1) Develop methods for generating odor plumes of defined structures in wind tunnels. Develop methods for analyses of flight tracks and maneuvers in 3-D. Establish how flying moths integrate information from odor, visual and wind inputs to trace an odor plume to its source. Develop methods to measure the fine-scale characteristics of odor plumes in our wind tunnel using a propylene-air mixture as a surrogate odor. Use electrophysiological measurements (at the antennal level with electroantennograms) to determine how well such signals are detected by our model insect species. (2) Develop computer-based models of odor dispersion and vehicle movement. Implement and evaluate insect-inspired strategies for plume finding, maintenance of upflow progress, plume reacquisition, and declaration that the odor source has been found. Implement and evaluate engineering-based plume tracing strategies.

ACCOMPLISHMENTS: Constructed a 3-m-long wind tunnel and versatile pheromone/surrogate odor-delivery system to simulate natural plume structure. Developed a system to measure the precise instantaneous structure of odor plumes, using a photoionization detector (miniPID) positioned precisely via a computer on a custom-built x,y,z traverse. Developed a video-computer system to record and analyze in 3-D, tracks of insects flying in the wind tunnel.

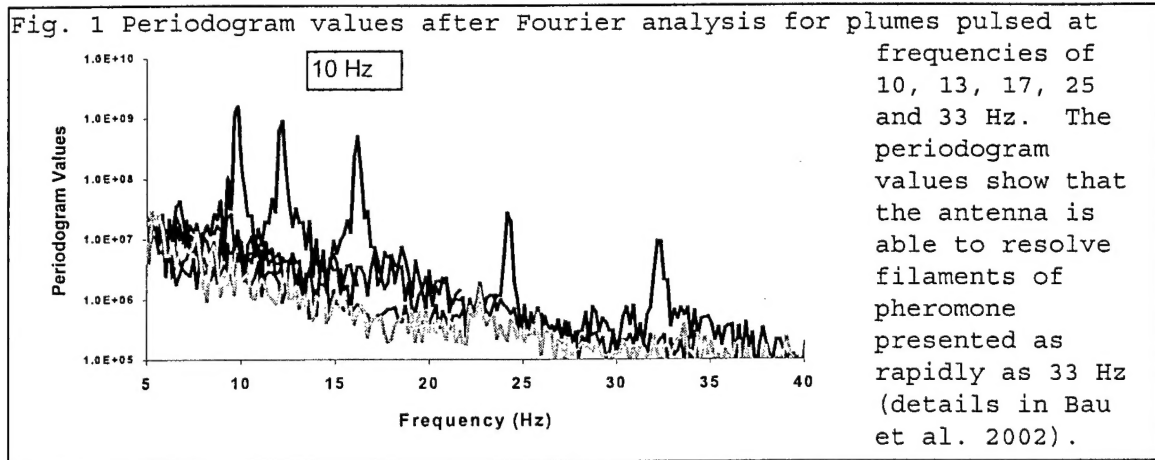
Our wind tunnel trials with the almond moth have confirmed that a signal of 10 Hz (or higher) frequency produces accelerated, nearly due upwind flight in this model insect (Justus et al. 2002b). We also have confirmed with our miniPID/propylene measurements that the structure of the plumes generated with our flow systems indeed is comprised of a precise, pulsed structure (Justus et al. 2002a), as assumed from previous observations with a visual tracer.

Entirely novel findings are that:

1. Moths head rapidly upwind in a homogeneous cloud of pheromone (Justus and Cardé 2002). This establishes that a 'flickering' signal is not requisite for orientation upwind. Males heading upwind, however, follow a trajectory on average 15° off due upwind. This unexpected maneuver may relate to our counterintuitive finding in simulations (point 7 below) that flight due upwind is generally not the most effective way to maintain contact with the plume while progressing upwind.
2. Moths can use an "aim-then-shoot" form of orientation (Wiesniewska 2001), in which a course trajectory is set while in flight, using visual

pattern below as a collimating cue. When moths remain within the plume's overall boundaries, they may head as much as 25° off due upwind, provided they continue to aim toward the same visual cues. This is an entirely new mechanism for in-flight orientation to odor, not predicted by conventional, odor-induced optomotor anemotaxis.

3. Males are capable at the antennal level of deciphering flickering signals up to 33 Hz, according to a Fourier analyses of signal perceived by male moths (Fig. 1, Bau et al. 2002). This capacity had not previously been assessed in any moth.



4. In another model system, flight of female mosquitoes to host-emitted odors, the structure of the plume also was found to be crucial. In the mosquito species that vector yellow fever mosquito and malaria, turbulent plumes of CO₂ evoked upwind flight, whereas homogeneous clouds of CO₂ evoked only activation. In contrast, the internal structure of skin odor plumes had little effect on their attractiveness (Dekker et al. 2001).

5. Moths "closing in" on an odor source ("declaring it found") slow their velocity, narrow their flight track, and then land on or very near the odor source, even if the odor source is not visually apparent. The systematic changes that occur along the plume as it is carried downwind offer ample features for detection of distance to the odor source (Justus et al. 2002a). The most probable cues, however, now appear to be changes in concentration and signal intermittency.

In nature plumes are difficult to trace because of two characteristics. First, plumes are very patchy because of turbulent diffusion. Second, a due upwind course while odor is detected does not lead to the plume's origin, because of plume meandering ("snaking") caused by changes in wind direction and velocity. Therefore, an initial task was to devise a computationally-feasible model which mimics the patchy nature of plumes in nature, complete with their overall meander. This model (see the snapshot in Fig. 2) and its concordance with field measurements of instantaneous plume structure are provided in Farrell et al. (2002). It is important to recognize that such a meandering plume is much more difficult to trace to its source than plumes generated in unidirectional flow systems, as is the case in most all wind tunnels and water flumes.

We have coupled our plume model with a spectrum of insect-inspired orientation strategies to see which of these are useful to guide

vehicles. Our simulations were over large areas (e.g., 100 by 100 m) and we used the rates of pheromone emission of the gypsy moth female and the threshold (or 10 times threshold) of response of the male gypsy moth to parameterize our runs. The full results of 1000s of simulations and several strategies of plume tracing are detailed in Li et al. (2002). The most salient findings of our simulations are that:

6. A generally crosswind movement strategy is optimal for initial contact of the plume.

7. Once detected, the "best" strategy for maintaining plume contact while progressing toward the odor source is to follow a counterturning

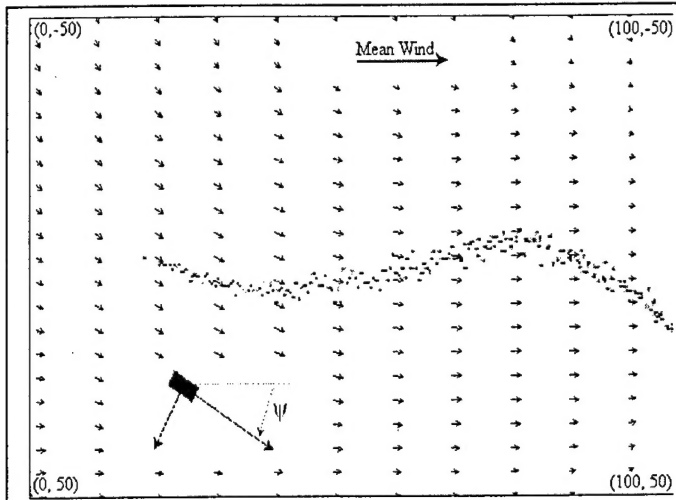


Fig. 2. Snapshot of simulated vehicle (not to scale) operating relative to a dispersing pheromone in a 100 by 100 m search area. The grey scale indicates above threshold concentration. Arrows indicate the local time varying wind vector at the tail of the arrow.

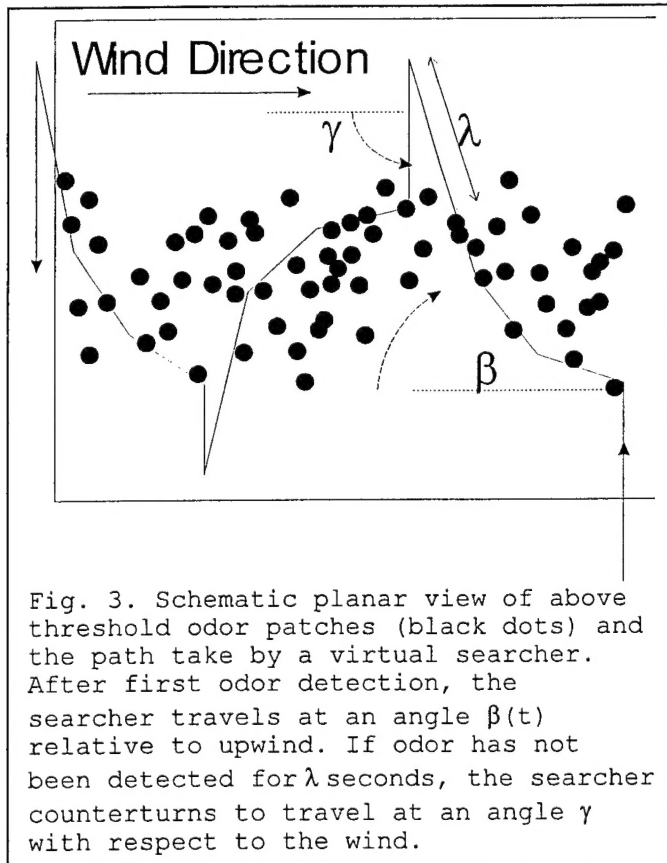
trajectory such as that depicted in Fig. 3. Upon the initial detection of the plume on a given transect, the searcher turns almost straight into the wind to attain up-plume progress. As the time from the initial detection of the present transect increases, the search assumes an increasingly crosswind direction of travel. This causes the searcher to leave the plume from the opposite side of the plume than it entered, with a high degree of certainty. Therefore, when the searcher reverses its crosswind direction of travel (i.e., counterturns), it

has a high probability of recontacting the plume. If recontact occurs, then the searcher repeats the counterturning maneuver in the opposite crosswind direction for the next transect.

8. If the searcher loses contact with the plume, then the best reacquisition strategy is to cast right and left of the windline for a set giving up time (GUT). The optimal GUT depends on the maneuverability characteristics (e.g., turning radius versus speed) of the searcher. A GUT of about 4 seconds seems optimal, given a searcher with maneuverability characteristics similar to a moth.

9. Within 10 m of the source, heading directly upwind while in the plume diminishes time to source contact, compared to the strategy described in #7. As presently implemented, the searcher cannot discern that it is within 10 m of the odor's source, and so it does not switch to the strategy of upwind flight.

SIGNIFICANCE: Our improved understanding of insect orientation offers new approaches to testing insect-inspired models of robotic navigation to a point source of odor. Although there is more to learn about how insects find odor sources and how plumes of odor are dispersed in wind,



we have sufficient information to test a range of simulation strategies. We have developed models that (1) simulate the dispersion of odors in the wind; (2) simulate insect-inspired strategies to find odor plumes and follow them to their source; and (3) utilize odor detection events and engineering analysis to generate maps of likely odor source locations. These simulation strategies are highly efficient in their ability to quickly and reliably locate odor sources, and in their conservation of energetic expenditure. We have a sufficient understanding to apply these algorithms to command robotic vehicles (flying or maneuvering on the ground) in the field.

PUBLICATIONS AND ABSTRACTS:

1. Dekker, T., W. Takken and R.T. Cardé. 2001. Structure of host-odour plumes influences catch of *Anopheles gambiae* s.s. and *Aedes aegypti* in a dual-choice olfactometer. *Physiol. Entomol.* 26:124-134.
2. Wisniewska, J. 2001. Influence of visual cues in the flight of male almond moths (*Cadra cautella*) within plumes of sex pheromone. Ph.D. Thesis, University of California, Riverside, 169 pp.
3. Farrell, J.A., J. Murlis, W. Lei and R.T. Cardé. 2002. Filament-based atmospheric dispersion model to achieve short time-scale structure of odor plumes. *Environ. Fluid Mech.* (in press).
4. Justus, K.A., J. Murlis, C. Jones and R.T. Cardé. 2002a. Measurement of odor-plume structure in a wind tunnel using a photoionization detector and a tracer gas. *Environ. Fluid Mech.* (in press).
5. Justus, K.A., S.W. Schofield, J. Murlis and R.T. Cardé. 2002b. Flight behaviour of *Cadra cautella* males in rapidly pulsed pheromone plumes. *Physiol. Entomol.* (in press).
6. Justus, K.A. and R. T. Cardé 2002. Flight behaviour of two moths, *Cadra cautella* and *Pectinophora gossypiella*, in homogeneous clouds of pheromone. *Physiol. Entomol.* (in press).
7. Cardé, R.T. 2002. Use of semiochemicals for survey and detection of exotic insects: principles and constraints. *Proceedings Plant Health Conference 2000: Detecting and monitoring invasive species.* USDA-APHIS-PPQ, Center for Plant Health Science and Technology, Raleigh, North Carolina. (in press).

8. Lei, W. J.A. Farrell and R.T. Cardé. 2002. Tracking of fluid-advected odor plumes: strategies inspired by insect orientation to pheromone. *Adapt. Behav.* (in press).
9. Bau, J., K.A. Justus and R.T. Cardé. 2002. Antennal resolution of pheromone plumes in three moth species. *J. Insect Physiol.* (in press).
10. Dekker, T., R.T. Cardé and W. Takken. 1999. The structure of host-odour plumes influence trap-entry response of mosquitoes. XII European meeting, Society for Vector Ecology, Wageningen, The Netherlands, September 8, 1999, Abstracts, p. 52.
11. Cardé, R. T. 1999. How does the structure of odor plumes influence the orientation of mosquitoes? Invited Symposium, First Asia-Pacific Conference on Chemical Ecology, Shanghai, China, November 2, 1999. Abstracts.
12. Cardé, R.T.. 2000. Mechanisms of Orientation of Moths Flying to Pheromone, Invited Keynote Lecture, 17th Annual Meeting, International Society of Chemical Ecology, Pocos de Caldas, Brazil, August 16, 2000. Abstracts, Oral, KS2.
13. Cardé, R.T. 2000. Sensory Inputs Governing Upwind Flight of Male Moths Along Pheromone Plumes, Invited Symposium, XXI International Congress of Entomology, Iguassu Falls, Brazil, August 23, 2000, Abstracts, p. 154.
14. Cardé, R.T. 2001. Chemical Signals in the Environment: Influences of Patterns of Encounter on Insects' Behavioral Responses. Invited Symposium. 18th Annual Meeting, International Society of Chemical Ecology, Lake Tahoe, California, July 8, 2001. Abstracts, p. 29.
15. Cardé, R.T. 2001. Video Methods for Behavioral Bioassays and Analyses. Invited Symposium. 18th Annual Meeting, International Society of Chemical Ecology, Lake Tahoe, California, July 10, 2001. Abstracts, p. 79.
16. Cardé, R.T. and T. Dekker. 2001. Flight of Mosquitoes in Odor Plumes. Invited Symposium. 3rd International Congress of Vector Ecology, Barcelona, Spain, September 21, 2001. Abstracts, p 67.